Hybrid Demand and Capacity Model for the Future Air Traffic Management Concept of Operations

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INNOVATING SOLUTIONS

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Background: GMV presentation

- Multinational conglomerate founded in 1984, private capital
- Headquarters in Spain, subsidiaries in Portugal and USA, and branch offices in Poland, Republic of Korea, and Malaysia
- Over 1,000 employees all over the world with an annual turnover of more than $120M
- Operating in Aeronautics, Space, Defense, Security, Transportation, Healthcare, and ITC industries.

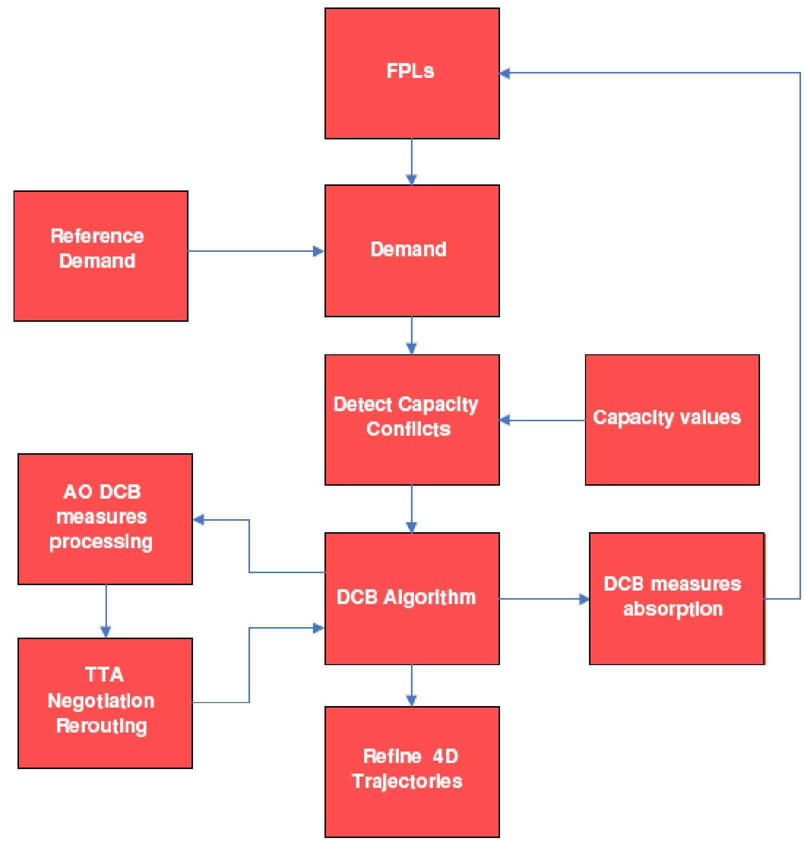
Background: Project context

- GMV initiative (company investment) to carry out a research project in the ATM domain in line with the trends in the European ATM R&D
- Special thanks to AENA for its involvement in the project (with its own internal resources) to provide key guidelines and feedback
- Coordination of the project with other ATM research activities carried out by GMV, in particular with the ATLANTIDA project

http://www.cenit-atlantida.org/portal/index_en.html

Future Demand and Capacity Balance Concept

- Consistent with the Short Term Network Planning EP3 DoD (SESAR ConOps)
  - Network management
    - Airspace & airport-in-the-network
    - Regional & Sub-regional actors
  - Traffic flow measures (TTAs) allocated through a queue management process
  - Rolling planning window
  - Performance-based operations (SLA)
  - Trajectory-based Operations
  - User Preferred Trajectories
    - TTAs absorbed by the users according to their priorities
    - Users negotiation process under severe capacity drop (UDPP)



Future Needs for Demand adjustment

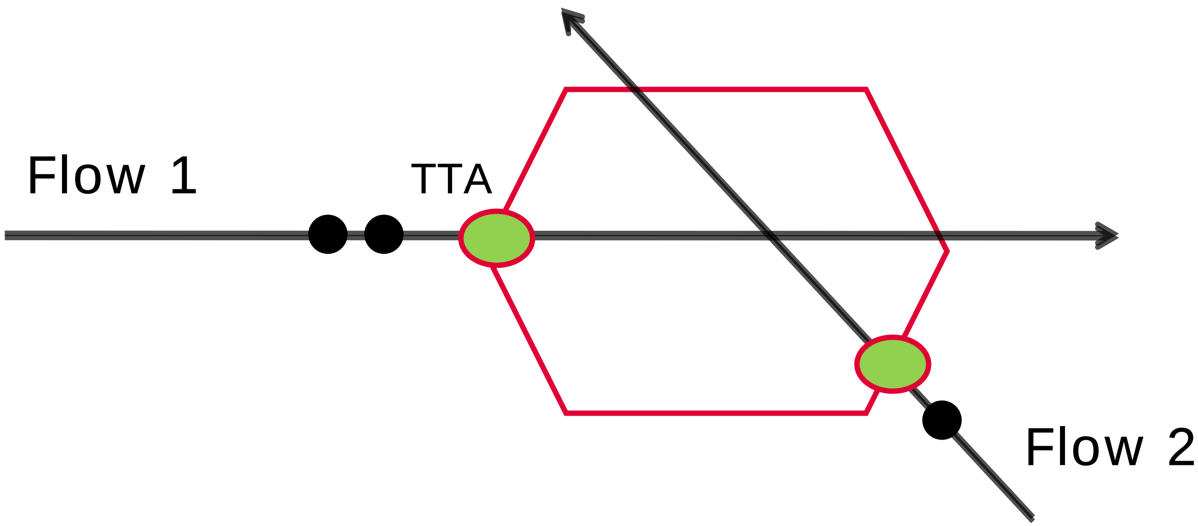
- The Demand adjustment optimization model must therefore
  - Integrate airports and airspace capacity (time dependant)
  - Generate constraints at any point (ground and airborne delays)
  - Obtain a solution that explicitly minimizes a given cost function
  - Be a trajectory-based system, capable of assigning the optimal TTAs to individual user trajectories (on ground and airborne)
  - Take into account user preferences (flight priorities)
  - Find a solution in a short computational time

Introduction to the Hybrid DCB Model (1/2)

- The presented model solves the air traffic network optimization problem (with multiple airports, sectors' and airports' capacity)
- Lagrangian air traffic flow measures (ATFM) are calculated for individual flights
- The core of the algorithm is a Pseudo-Eulerian-Lagrangian flow model
- Near-optimal individual ATFM measures are calculated in a short computational time. En-route and ground delays may be calculated
- Queue synchronized outputs in each constraint area (airspace/elementary volumes and airports) are obtained by the algorithm
- User preferences can be taken into account

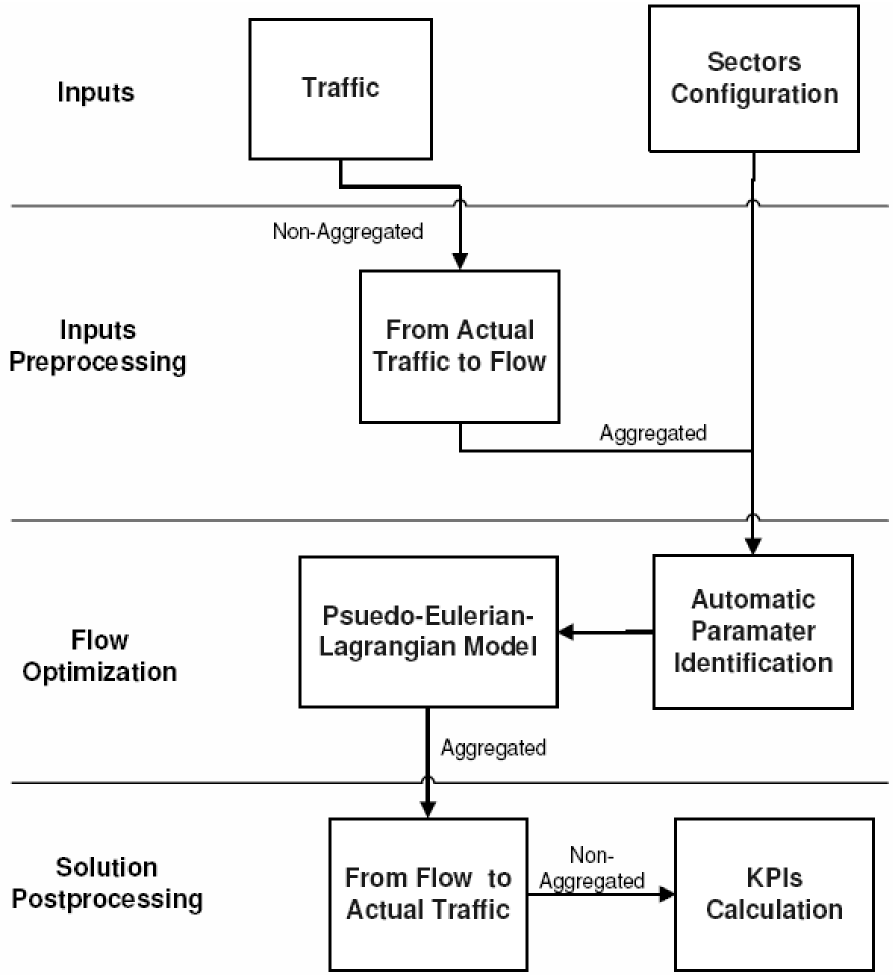
Introduction to the Hybrid DCB Model (2/2)

- The air traffic measures will be given to airspace users as a set of space-time constraints on the overloaded airspace/airport area (TTAs)
- The model manages a large amount of information; consequently, Key Performance Indicators are easy to calculate from it



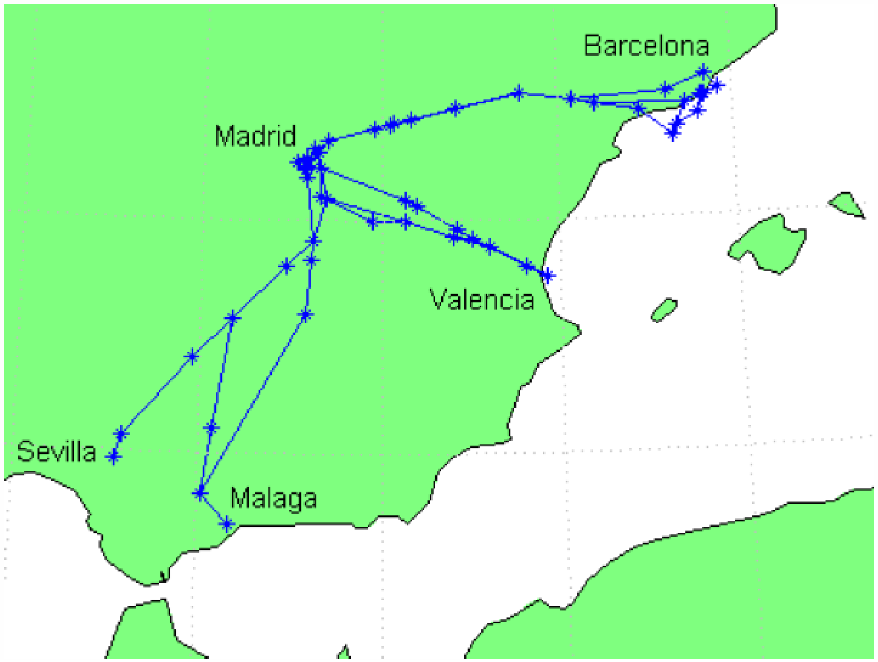
Hybrid DCB Model Information Flow

- The model manages Aggregated and Non-Aggregated data
- Conversion algorithms are required
- The optimality of the solution depends on the validity of a set of assumptions



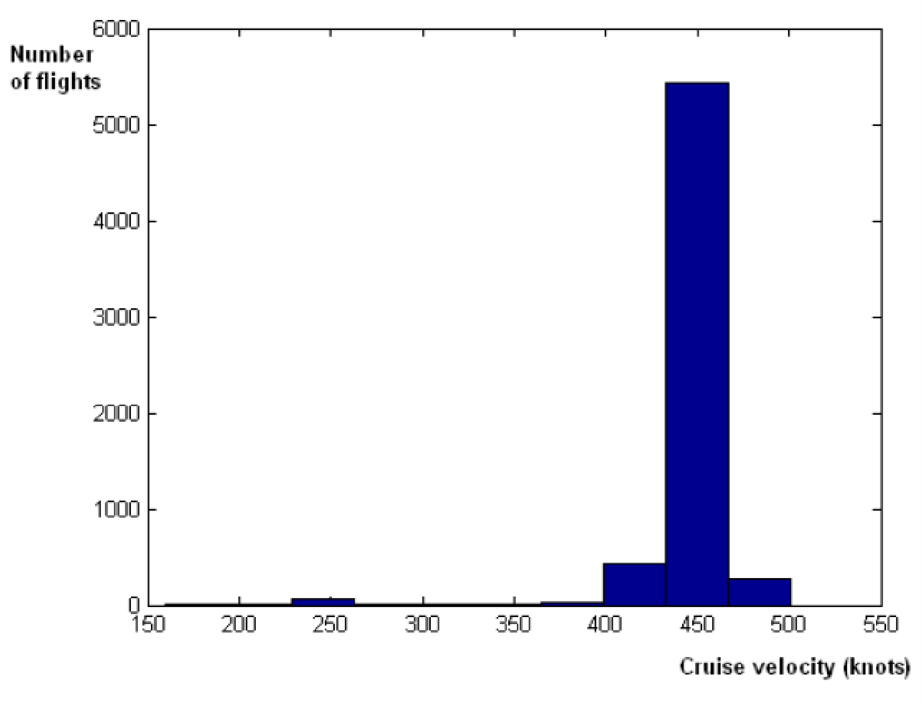
From Actual Traffic to Flows (1/2)

- The conversion to flow requires some approximations
- The aim is to model actual traffic data as a reduced number of *flow-based trajectories* (sharing route, altitude, velocity, and origin/destination airport)
- Due to the nature of the air traffic management problem, the aggregation is possible
- Is the conversion to flow worth it?

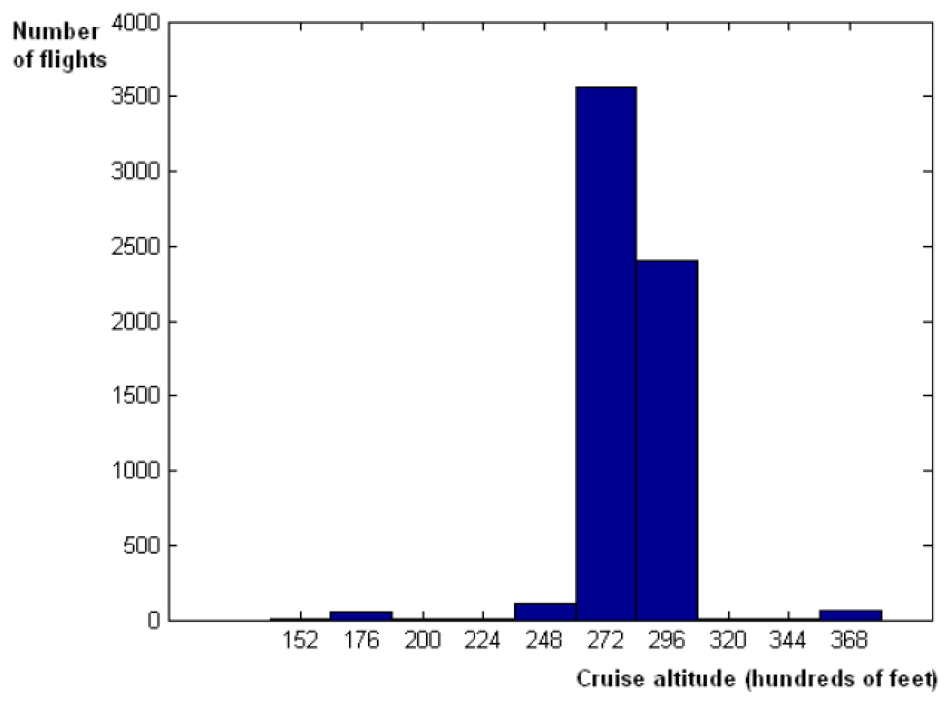


Routes from Madrid to four Spanish airports.

From Actual Traffic to Flows (2/2)



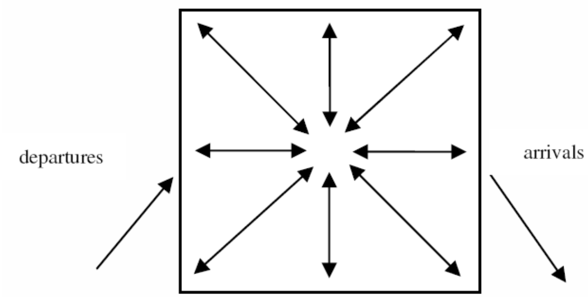
Cruise velocity distribution for flights travelling from Madrid to Barcelona (3-month period).



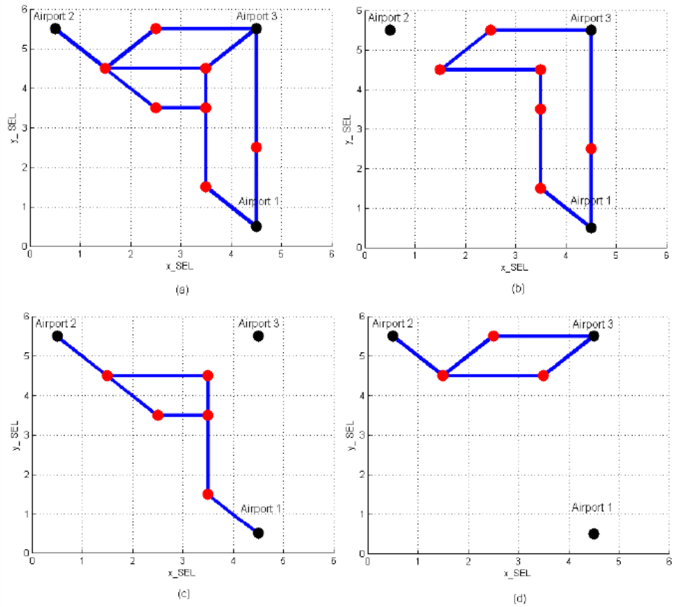
Cruise altitude distribution of flights travelling from Madrid to Barcelona (3-month period).

Pseudo-Eulerian-Lagrangian Model (1/2)

- It is the core of the Hybrid DCB Model
- The output of the algorithm is a set of air and ground flow-based delays
- The previously calculated *flow-based trajectories* are aggregated into *flow-planes*, which share the same collection of variables
- Control volumes occupying the same airspace can be modeled differently
- Flow-planes considerably reduce diffusion and dispersion problems of the Eulerian models
- Our purpose is to reach a trade off between the computational effort and the accuracy of the model



SELs streams.



Pseudo-Eulerian-Lagrangian Model (2/2)

- The model can be written as time-varying difference equation
- The problem is solved with the Model Predictive Controller technique
- Minimizing the weighted sum of all air and ground delays
- The constraints of the problem are the capacity constraints (sectors' and airports' capacity), system dynamics, and operational constraints
- The resulting MILP is relaxed to an LP problem

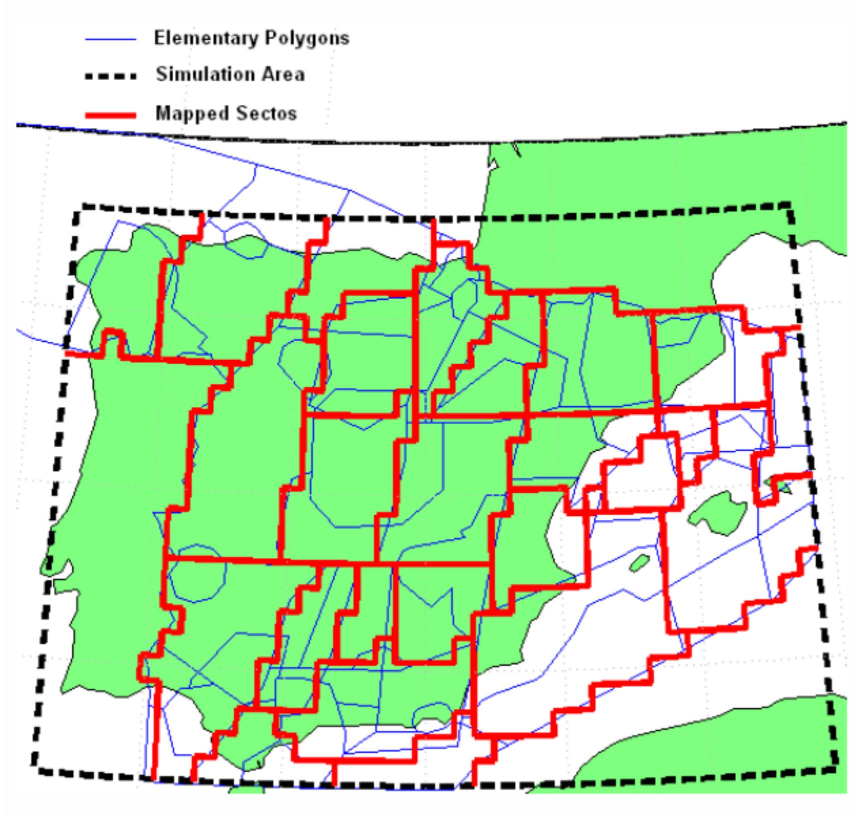
$$
\begin{aligned}
x_{(i,j,1)}(k+1) &= x_{1(i,j,1)}(k+1) + \cdots + x_{p(i,j,1)}(k+1) \\
&= a_{1(i,j,1)} \sum_{m \in s_{1(i,j)}} \beta_{1(i,j,1,m)} x_{1(i,j,m)}(k) \\
&\quad + u_{1(i,j,1)}(k) + y_{1(i-1,j,1)}(k) + (q^{depart}_{1(i,j,1)}(k) \\
&\quad - u^{ground}_{1(i,j,1)}(k)) + q^{exo}_{1(i,j,1)}(k) + \cdots \\
&\quad + a_{p(i,j,1)} \sum_{m \in s_{p(i,j)}} \beta_{p(i,j,1,m)} x_{p(i,j,m)}(k) \\
&\quad + u_{p(i,j,1)}(k) + y_{p(i-1,j,1)}(k) + (q^{depart}_{p(i,j,1)}(k) \\
&\quad - u^{ground}_{p(i,j,1)}(k)) + q^{exo}_{p(i,j,1)}(k) \qquad (1)
\end{aligned}
$$

$$x(k+1) = A(k)x(k) + B_1(k)u(k) + B_2(k)q(k)$$

$$y(k) = C(k)x(k) + D(k)u(k)$$

Automatic Parameter Identification Tool

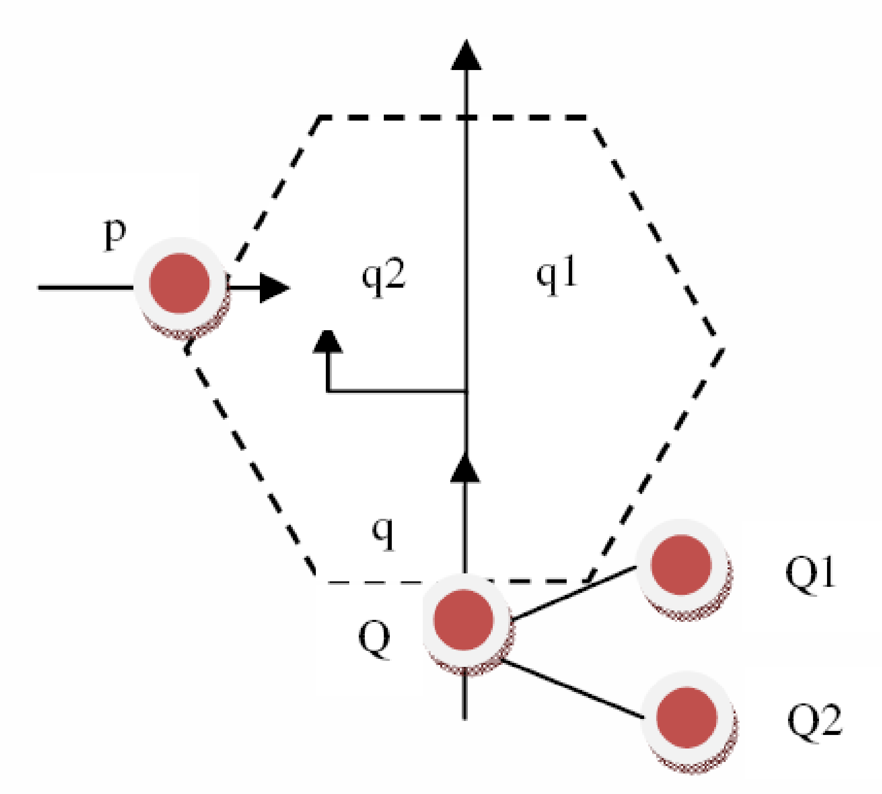
- The configuration of the presented model is not an easy task; it can not be done manually
- First, each SEL is mapped to a certain sector. Sectors modeling accuracy depends on the SELs size
- Next, traffic parameters are calculated. Waypoints are approximated to the nearest SEL center. And, *flow-based trajectories* are obtained
- The model parameters are calculated for each *flow-plane*



Sectors as SELs aggregation.

From Flow to Actual Traffic (1/2)

- Individual ground and en-route delays need to be calculated from the obtained flow controls
- Capacity constraints must be met
- The algorithm uses each constraint area input flow as a reference to follow
- Each constraint area input is modeled as a queue. Each queue throughput will be given by the solution computed by the Pseudo-Eulerian-Lagrangian flow model
- Each *flow-based trajectory* will have an associated queue



From Flow to Actual Traffic (2/2)

- Ensuring that each Lagrangian queue throughput is lower or equal to the calculated flow value, the capacity constraints will be met
- Queues are active when flow delays are calculated. Diffusion parameters need to match high traffic density scenarios
- The Hybrid DCB model will give the airspace users a set of time space constraints

$$if\ QOT > ETA\ \ then\ TTA = QOT$$

- The target time of arrival (TTA) will be absorbed by the users according to their priorities
- The obtained individual flights solution is near-optimal, but it is obtained in a short computational time

User Preferences in the Hybrid DCB Model

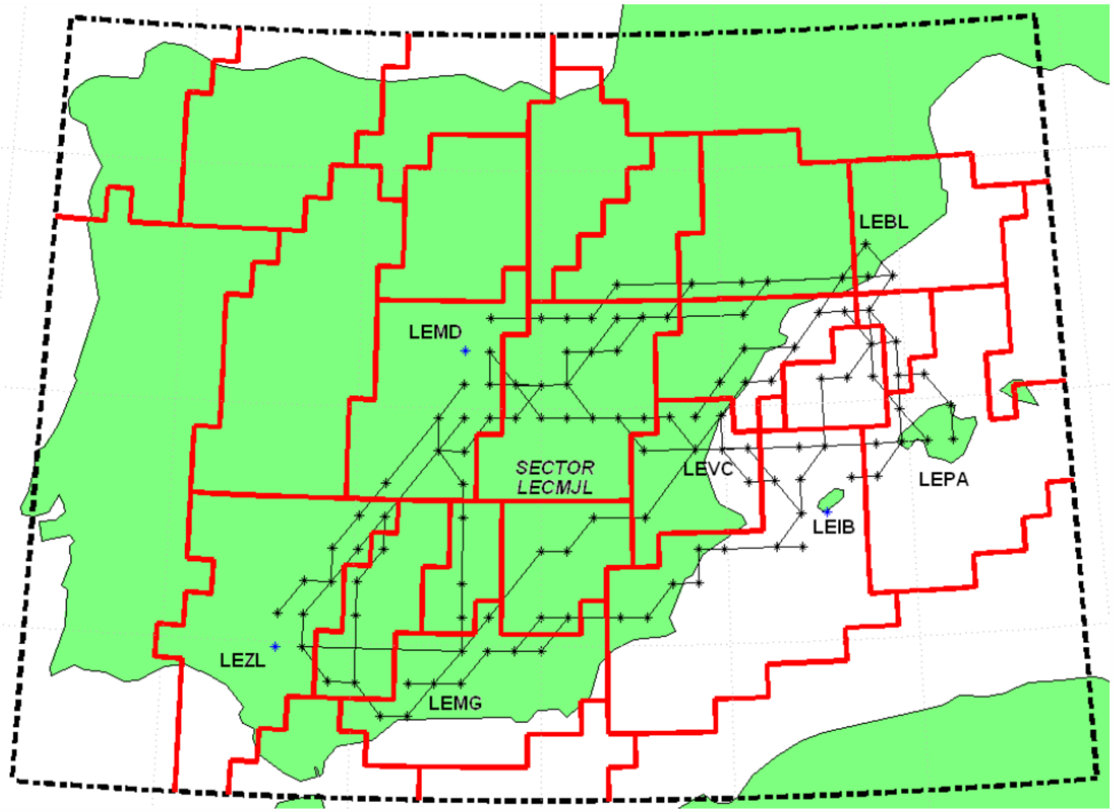
- User preferences can be taken into account at two different levels:
  - ***Inter-flow preferences***: the delays calculated for each flow stream in the model may have different weights associated with them in the cost function
  - ***In-flow preferences***: any queue priority discipline can be implemented in the flow to individual flights conversion algorithm, without affecting the queue's throughput

Key Performance Indicators

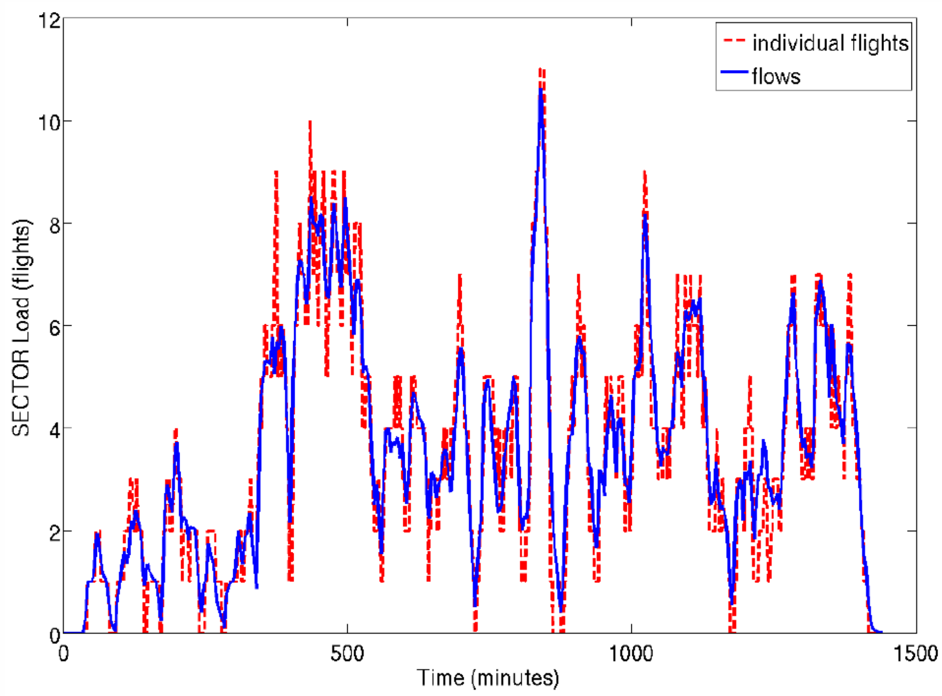
- In the new performance-based framework, the definition of a set of metrics is essential
- It is straightforward to extract data from the proposed model for the calculation of a set of KPIs, which give a good picture of the model performance:
  - Number of aircraft entering a sector per time step
  - Maximum number of aircraft present simultaneously in a sector
  - Total en-route delay for each flight
  - Sector load in each sector over time as a percentage of the maximum load
  - Total network en-route delay
  - Number of aircraft landing in each airport each time step
  - Number of aircraft departing in each airport each time step
  - Delay of each flight at the arrival airport
  - Total arrival delay in the network
  - Delay of each flight at the departure airport
  - Total departure delay in the network
  - Difference between the target time of arrival of each flight to each sector and the initially planned time

Simulation Results (1/3)

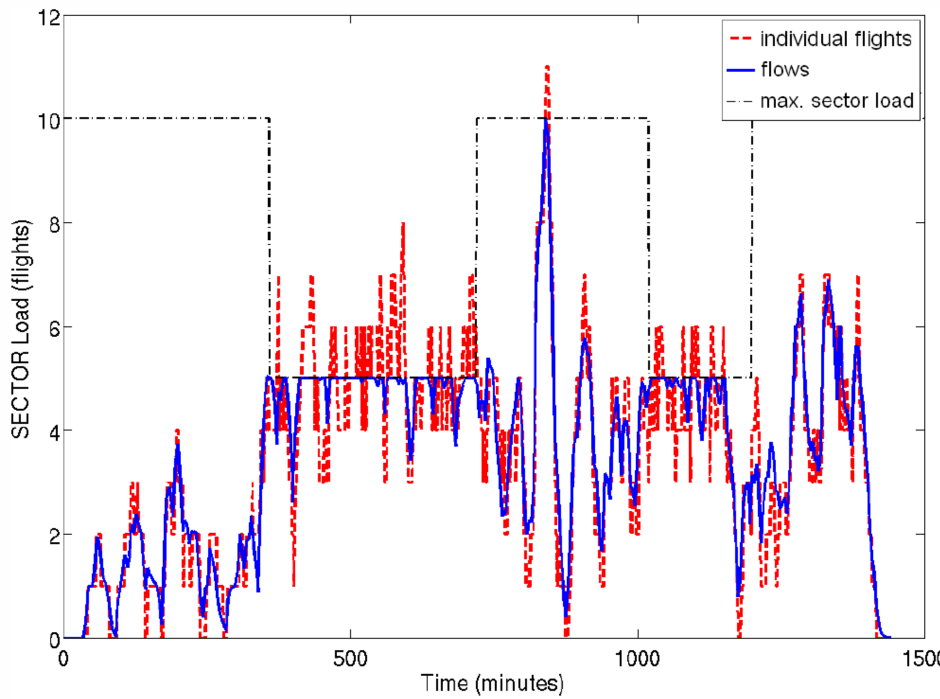
- The scenario shows the performance over a one-day planning period
- The simulation scenario is composed of 20 *flow-based trajectories*, 28 sectors and 7 airports
- The scenario leads to 144 occupied SELs
- The MPC look ahead time affects the optimality of the solution and the computational requirements (we chose 40 min.)



Simulation Results (2/3)



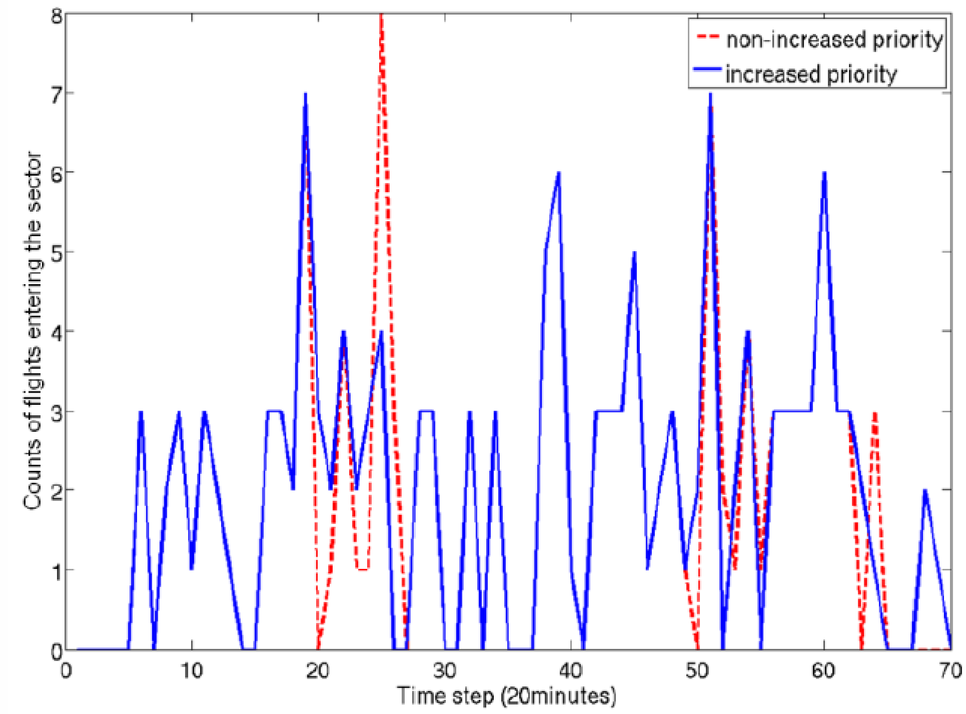
Instantaneous load of sector LECMCJ with no ATFM measures.



Instantaneous load of sector LECMCJ under dynamic maximum sector load.

Simulation Results (3/3)

- Some post-processing may be needed to eliminate transient effects
- FC/FS was the queue discipline considered in the simulation
- Each MPC iteration was solved in less than 1 minute
- Real time implementation is possible for this scenario (4-minute time step)



Model Applications

- Validate new operational concepts (run validation exercises)
  - Short term changes to current ConOps (e.g. DMEAN)
  - Mid/Long term changes (SESAR/NextGen)

- Monitor network performances in the execution phase
  - Performances forecast (monitor compliance with SLA)
  - Assess network effects (what-if / sensitivity analysis)
    - Demand uncertainty
    - Rerouting scenarios
    - Service Level Agreement (objective function to optimize)

Next Steps

- The presented analytical model was developed in Matlab-Simulink environment that imposes severe software limitations on the size of the exercise to run: partial re-engineering (*e.g.*, use of sparse matrices) or re-coding of the model may be necessary

- From a model point of view, the key research areas are
  - More work should be done on the aggregation of the *flow-based trajectories, since the a*ggregation of the *flow-based trajectories* reduces the number of variables in the problem, but the lack of stability on the diffusion parameters matching actual traffic data can introduce undesired errors
  - Study how the users' inter-flow and in-flow priorities affect the solution performance by studying the defined KPIs under different sets of priorities
  - Study the stability of the users' TTAs absorption process

Thank you

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